

# Calibrating cosmological chronometers: white dwarf masses via astrometry

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## Abstract.

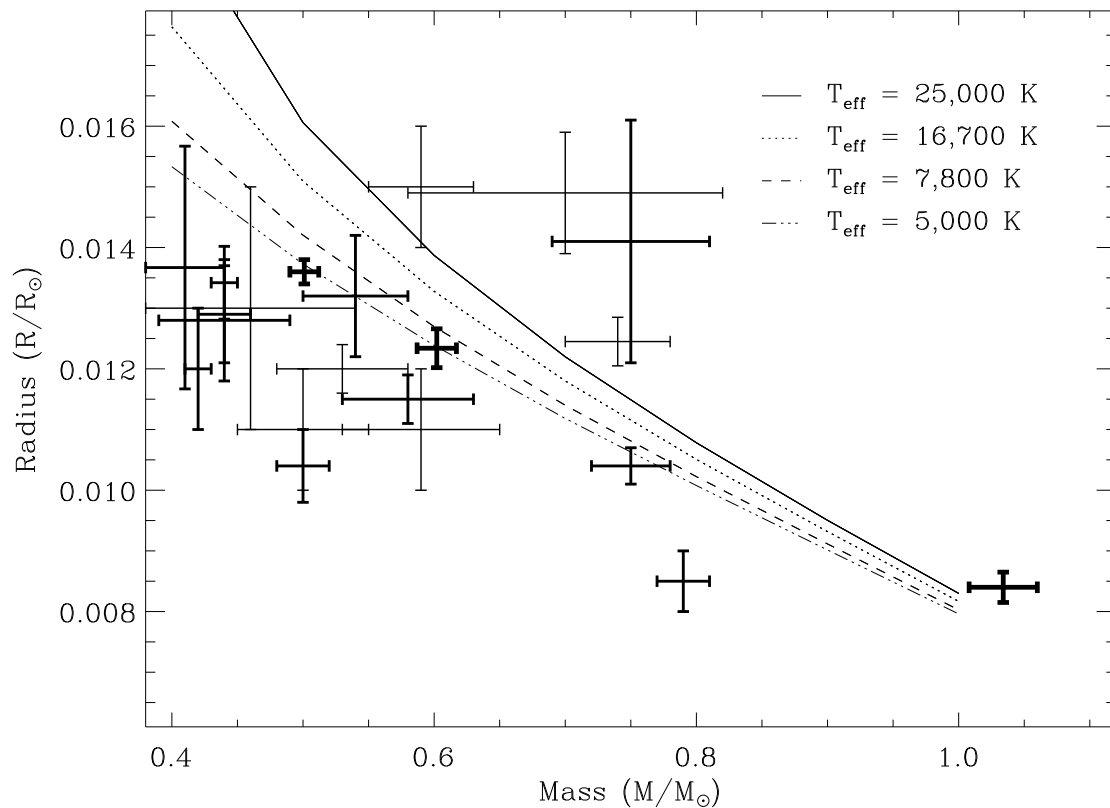
In an effort to increase the number of accurate dynamical masses for white dwarfs (WDs), we have begun an initiative using *Hubble Space Telescope's* Fine Guidance Sensors (FGS) to resolve suspected binary WDs. With the increasing number of WD trigonometric parallaxes becoming available via CTIO's and the USNO's ongoing parallax programs, we have targeted objects that are overluminous at  $V$  magnitude and are presumably unresolved multiple systems. A few targets were selected because of spectral anomalies or possible perturbations evident in the residuals of the trigonometric parallax solutions. A total of 16 HST orbits were designated to this program and 12 are completed. Of the eleven WDs observed thus far (one object was observed twice), all but one were unresolved. Analysis of a recent orbit's data indicate a pair was resolved with a separation of 70 mas and a delta  $V$  magnitude of  $\sim 1.4$ . Coupled with astrometric data from the USNO parallax program, we have obtained preliminary constraints on component masses.

## 1. Introduction

White Dwarfs (WDs) are, in general, rather well understood physically and thus, serve as proxies to astrophysically compelling questions regarding ages. For instance, WDs have been used to gauge the ages of the nearest globular clusters (Hansen et al. 2004, 2007) as well as the age of the Milky Way's thick disk (Reid 2005 and references therein). The two components needed to model WD age are effective temperature and mass. The effective temperature can be obtained by spectral energy distribution fitting to the photometry and/or spectroscopy and the mass is usually obtained by invoking the theoretical mass-radius (M-R) relation (using the radius obtained either by spectral line fitting or trigonometric parallax). The M-R relation is dependent on the internal composition of the WD (either pure or a mixed combination of He, C, N, Ne, Mg, or Fe). Thus, WD masses need to be determined accurately and independently to stress test the theoretical M-R relation and reveal the true chemical makeup of WDs. The most direct method of determining accurate masses is to astrometrically map orbits of binary systems.

To date, only three WDs have dynamical masses determinations known to better than 5% (Sirius B, Procyon B, and 40 Eri B, Provencal et al. 2002). While these three cover a fairly broad range of masses (on the low end,  $0.50 M_{\odot}$  for 40 Eri B, and on the high end,  $1.02 M_{\odot}$  for

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**Figure 1.** Current empirical confirmations of the theoretical M-R relation reproduced from Provencal et al. (2002). The objects included are the three mentioned in the text that have dynamical mass determinations (*extra-thick bars*), eleven are field WDs with masses derived from spectral modeling (*thick bars*), and seven are members of wide common proper motion binaries whose masses were determined via gravitational redshift (*thin bars*). Theoretical curves for the four temperatures listed are derived from the Wood (1995) C/O-core models with  $10^{-4}$  fractional H and  $10^{-2}$  fractional He layers.

Sirius B), they hardly provide a robust empirical confirmation of the theoretical M-R relation. To scale projected dimensions to true dimensions (necessary to constrain the sum of component masses), an accurate distance determination via trigonometric parallax is necessary. Thus, it is not surprising that these three systems rank among the 50 nearest systems to the Sun (Sirius AB = fifth, Procyon AB = thirteenth, and 40 Eri ABC = fiftieth, [www.recons.org](http://www.recons.org)). In fact, the largest component of the error budgets of Sirius B's and 40 Eri B's mass determinations are the uncertainties of the parallaxes (Provencal et al. 1998). It is necessary to probe nearby WDs for companions and ultimately obtain dynamical masses and independent checks on the fundamental and widely used theoretical M-R relation.

## 2. Current mass-radius relation

There currently exists 21 empirical checks to the theoretical M-R relation with varying degrees of quality (see Figure 1). However, as mentioned previously, only 3 have masses known to better than 5%. Eleven WDs have masses determined based on spectroscopic analyses coupled with trigonometric parallaxes. In effect, observed spectra are compared to synthetic spectra derived from model atmospheres to obtain estimates of  $T_{\text{eff}}$  and  $\log g$ , the latter being constrained

by the parallax. This method is limited to those WDs with accurate trigonometric parallaxes and suffers drawbacks. Uncertainties include pressure effects that lead to overestimated values of  $\log g$  (i.e., the presence of trace amounts of He), the importance of and ability to model temperature-dependant convective properties, the reliability of broadening theory, and the inherent uncertainties of the observationally constrained parameters (Provencal et al. 1998).

Seven WDs are members of wide common proper motion systems. In these cases, the radial velocities are measured for both components (the non-WD components are usually red dwarfs) with the assumption that any orbital motion is negligible. Thus, any difference between the measured radial velocities of the components is attributed to the gravitational redshift of the WD, hence a mass determination is possible (when coupled with a radius determined via trigonometric parallax). The drawback with these systems is their distances. They are, on average, more distant than the visual binaries and as such, the fractional parallax errors (i.e., parallax error relative to parallax) are larger and correspond to larger mass errors. As is evident in Figure 1, all but the three dynamical mass determinations are of limited use as empirical checks to the theoretical M-R relation.

### 3. Identifying new candidate double degenerate systems

A double degenerate (DD) system is one that contains two WDs in orbit around each other. Such systems can be extremely useful to test the theoretical M-R relation because, when the orbit is mapped (and the distance is determined), dynamical masses can be obtained for two WDs at once. However, as a consequence of binary evolution, DDs are often found in short period systems because their progenitors filled their Roche lobes as they evolved off of the main sequence. Thus, they underwent a common envelope phase where friction inside the envelope drastically decreased the binary separation. The orbital energy and angular momentum removed from the system during the process then expelled the envelope revealing the two components. Additional angular momentum loss via gravitational radiation further degraded the orbit such that periods range from hours to days (Rebassa-Mansergas et al. 2008). Thus, there is a bimodal distribution of DDs with those that underwent a common envelope phase having very short orbital periods and those that essentially evolved as single stars having periods of decades to centuries.

Post-common envelope binary WDs are rather common ( $\sim 100$  with known orbital periods, Morales-Rueda et al. 2005) yet because of their highly interactive pasts (the details of which are not fully understood), they are not good candidates for empirical checks of the theoretical M-R relation. Instead, those systems whose components evolved as single stars are more relevant to test the M-R relation given that this relation is invoked to estimate the masses of single field WDs. However, finding such systems with orbital periods that are not prohibitively long such that the system's orbital parameters can be sufficiently constrained is non-trivial.

In general, one must exclude any system that is resolved by standard ground-based imaging<sup>1</sup>. As previously mentioned, proximity to the Sun is important to minimize the fractional parallax error as this is often the largest contribution to the mass error budget. We have targeted nearby WDs for a more thorough evaluation in search of DD systems.

#### 3.1. Overluminous white dwarfs

As part of the southern hemisphere parallax program, CTIOPI (Cerro Tololo Inter-American Observatory Parallax Investigation), we have added 35 new WD systems to the 25 pc sample (horizons of the Catalog of Nearby Stars and the NStars database) thus far in addition to

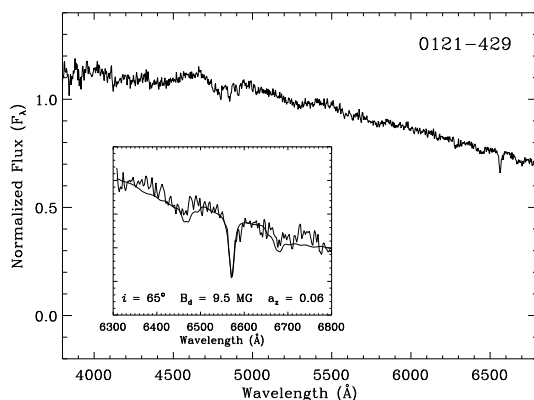
<sup>1</sup> Although 40 Eri B is resolved, the orbital period is  $\sim 250$  years and we have yet to observe one complete orbit. Its proximity to the Sun ( $5.03 \pm 0.02$  pc, [www.recons.org](http://www.recons.org)) and the fact that it has been observed since 1851 allows for an accurate mass determination.

measuring accurate parallaxes to a number of WD systems beyond 25 pc. With accurate trigonometric parallaxes available, we generated a Hertzsprung-Russell (H-R) diagram, including the known sample of WDs with parallaxes from Bergeron et al. (2001). In some cases, there are a few WDs that lie above the locus of the rest, thus implying that they are overluminous. There are two obvious scenarios that would lead to a WD being overluminous, (1) the object is an unresolved DD with each component contributing to the total flux, or (2) the object is a very low mass WD with a large radius and hence a relatively large luminosity. The second scenario is limited by the age of our Galaxy such that the lowest-mass WD that could be formed via single star evolution is  $\sim 0.47 M_{\odot}$  (Iben & Renzini 1984)<sup>2</sup>. Given that the first scenario is the more likely, the apparently overluminous WDs are potentially resolvable DD systems.

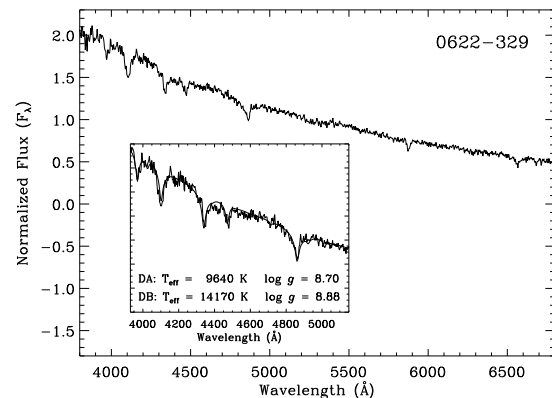
### 3.2. White dwarfs with spectral anomalies

During co-author Subasavage's spectroscopic search for new WD discoveries in the southern hemisphere, two spectra show anomalies that hint at the possibility that the spectra are convolutions of two different WD components. The first (WD 0121–429) is a cool hydrogen-rich DA WD that exhibits Zeeman splitting of  $H\alpha$  and  $H\beta$  indicative of a magnetic field on order of 9.5 MG (Subasavage et al. 2007). The trigonometric parallax obtained via CTIOPI implies that if this object is a single star, its mass is  $0.43 \pm 0.03 M_{\odot}$  which is unlikely to form via single star evolution as discussed earlier. Also, the spectral fit to the central line of  $H\alpha$  (the strongest and most important to model correctly) requires a 50% dilution factor (see Figure 2). This can be interpreted as a DD system with one component being a magnetic DA WD and the other component being a featureless DC component.

A second object (WD 0622–329) is classified spectroscopically as a DAB WD (prominent hydrogen lines with weaker He lines). However, it is not possible to model the spectrum with a single temperature. By assuming the spectrum is a convolution of two WDs of different temperatures, the fit is much better (see Figure 3). Thus, it is likely that this system is comprised of a hotter DB WD and a cooler DA WD (Subasavage et al. 2007).

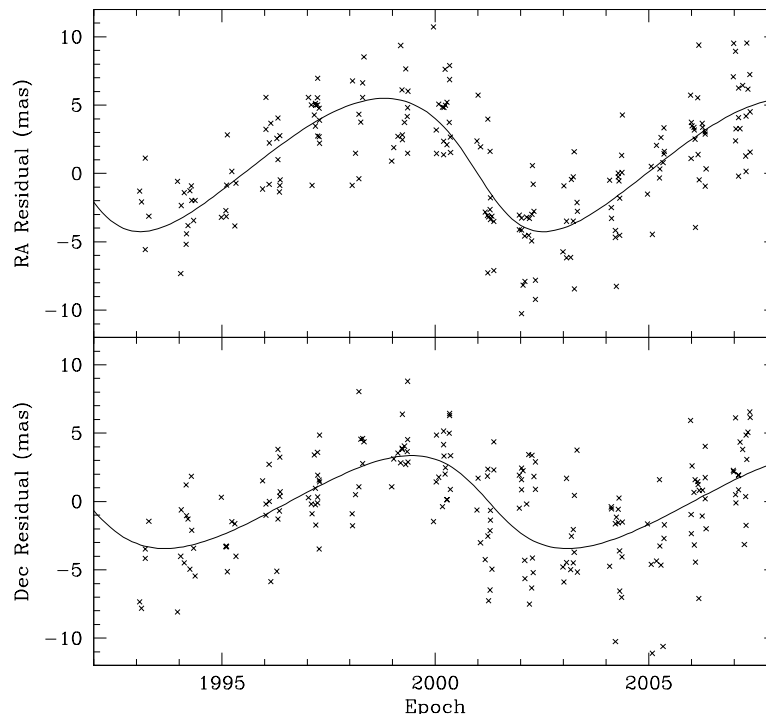


**Figure 2.** Spectral fit for WD 0121-429 (*inset plot dark line*) including a 50% dilution factor.



**Figure 3.** Spectral fit for WD 0622-329 (*inset plot dark line*) assuming an unresolved double degenerate.

<sup>2</sup> We note that recent work by Kilic et al. (2008) suggests that WD masses lower than this can be formed via single star evolution in the solar neighborhood. It is proposed that a relatively metal-rich progenitor may undergo significant mass loss while on the red giant branch such that it will never ignite He and thus continue its evolution as a lower mass He core WD. This scenario would allow for a single star's minimum mass to be  $\sim 0.40 M_{\odot}$ .



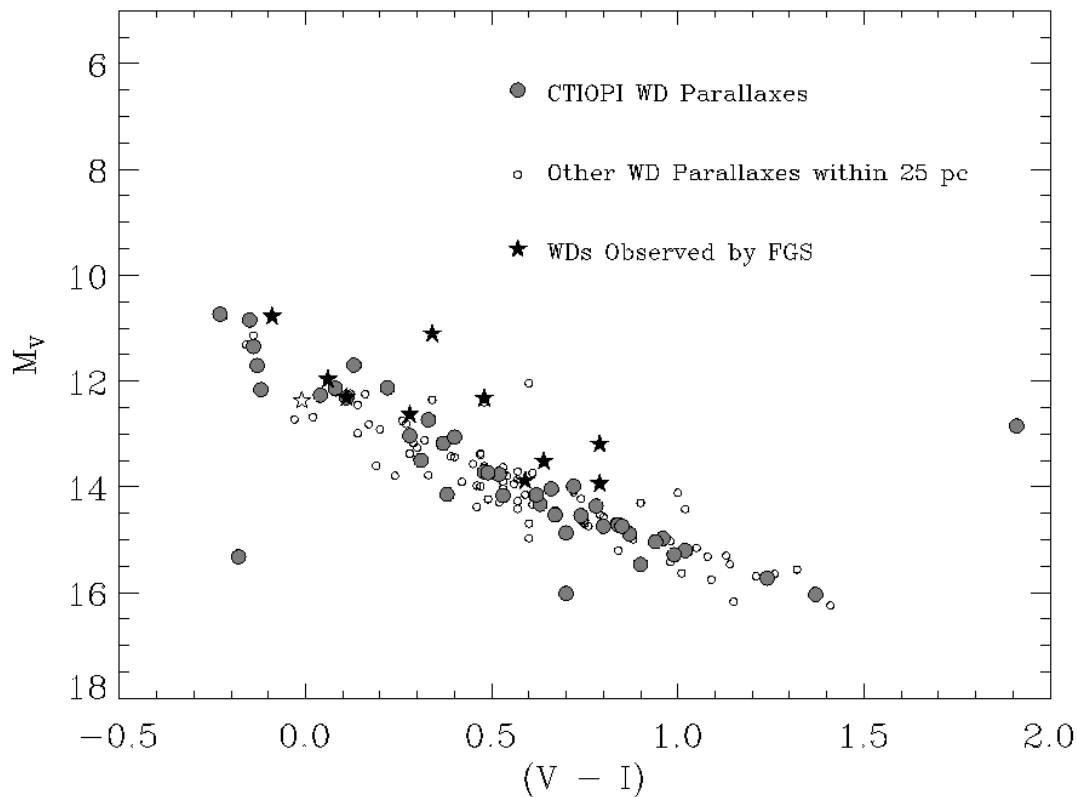
**Figure 4.** Plot of the residuals for WD 1132+470 once proper motion and parallax are fit and removed as well as a best-fit orbit (*solid line*).

### 3.3. White dwarfs with apparent astrometric perturbations

Ongoing trigonometric parallax programs both at CTIO and USNO have collected data on numerous nearby WDs that span several years (in some cases on the USNO program, more than a decade). On a rare occasion, once proper motion and parallax have been fit to the astrometric data and removed, there is an indication of a periodic perturbation caused by an unseen companion. On the CTIOPI program, it was thought that three such WD systems were identified; however, it was recently determined that they were erroneous signatures. The Johnson *V* filter used at CTIO to obtain parallax data since 1999 cracked in early 2005. Thus, a different (though similar in terms of transmission) Johnson *V* filter replaced the cracked filter. This caused a slight shift in the centroids that resulted in a “dip” in the residuals by  $\sim 5$  mas for mid-2005 data. As more data were collected, the residuals began to resemble sinusoidal arcs as a consequence of the parallax fitting routine attempting to fit this dip. This was not noticed to be a systematic effect until years later when there was sufficient post-filter-switch data that the dip was clearly evident in numerous *V* filter targets. Once all targets with possible perturbations that were observed in *V* are eliminated, there are no obvious perturbations with periods less than  $\sim 5$  years.

However, one target (WD 1132+470) on the USNO program that has been observed for  $\sim 15$  years, shows a clear periodic trend in the both right ascension and the declination residuals<sup>3</sup>. These data indicate a period of  $\sim 9$  years and a photocentric semi-major axis of  $\sim 6$  mas (see Figure 4). There is an ambiguity as to the nature of the companion based solely on these signatures. It could be either (1) a nearly equal mass, equal luminosity object, or (2) a substantially lower mass, lower luminosity object. If the first scenario is correct, this DD system is a prime target for measuring WD masses.

<sup>3</sup> A second USNO WD target shows a similar trend but was not analyzed in this work.

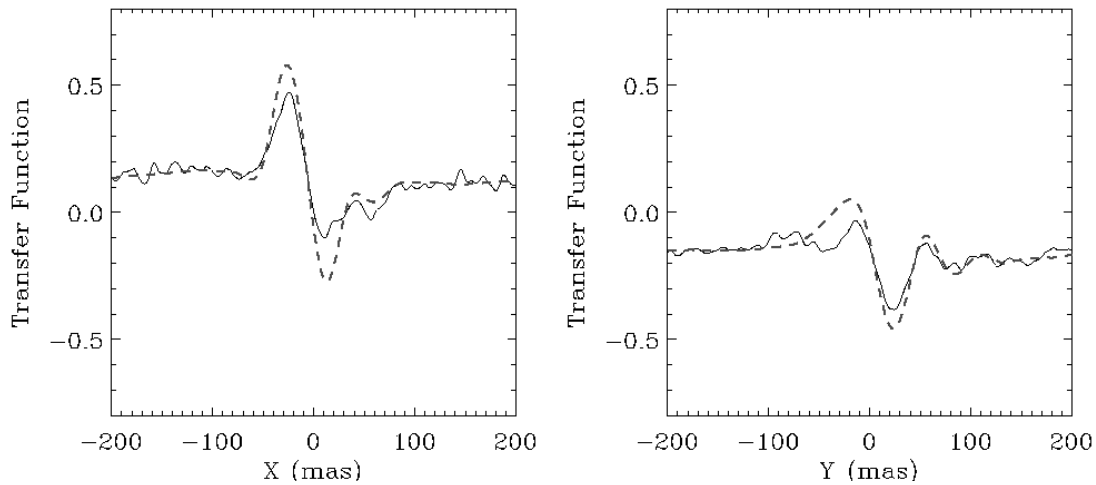


**Figure 5.** WD region of the H-R diagram. Plotted are WDs from the CTIOPI program (*filled circles*), known WDs within 25 pc from Bergeron et al. 2001 (*open circles*), and WDs observed with FGS via this effort (*filled stars*). WD 1132+470 is plotted as an open star.

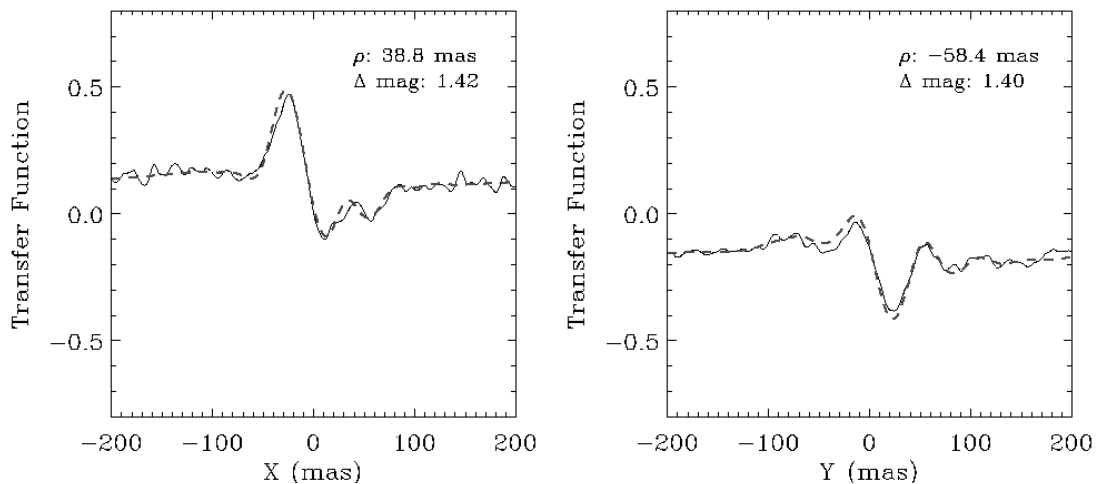
#### 4. Astrometric measurements using *HST*'s Fine Guidance Sensors

The Fine Guidance Sensors (FGS) on board *Hubble Space Telescope* (*HST*) are responsible for precision guiding of the telescope during observations that utilize other science instruments. Thus, it is a high precision astrometric instrument. It is also capable of stand-alone astrometric observations because there are three individual sensors, one that can be positioned on the target of interest while the other two provide guiding. It can acquire targets as faint as  $V = 16.6$  and can resolve companions with separations as small as 10 mas (assuming modest  $\Delta\text{mag}$ ). Translating these values into physical units, FGS would resolve an equal magnitude DD system at 25 pc with separations larger than 0.25 AU.

A total of 16 orbits spread over *HST* cycles 15 and 16 were awarded to this effort to resolve probable DD systems. To date, 12 are completed with 11 objects observed (one was observed twice) and are plotted in the H-R diagram in Figure 5. Of the 11 objects observed, only one was definitively resolved (WD 1132+470), and another was marginally resolved (WD 0121–429). In the second case, the signature may due to the evolution of the Y-axis fringe so a single star calibrator taken close in time to the target observation is needed to determine the degree of evolution. Another orbit has been assigned to this target as a safe measure. It is possible that the apparently overluminous targets that were unresolved are short period post-common envelope binaries. High resolution radial velocity measurements are necessary for confirmation.



**Figure 6.** Fringes in both axes for WD 1132+470 (*solid line*) vs. those of a single star calibrator scaled to the same magnitude (*dashed line*).



**Figure 7.** Fringes in both axes for WD 1132+470 (*solid line*) as well as the binary model fit (*dashed line*).

#### 4.1. WD 1132+470 results

By comparing the fringes in both axes of WD 1132+470 to that of a single star calibrator of the same magnitude (see Figure 6), it is clear that a second luminous source is distorting the profile of the fringes. Once a binary model is fit to the fringes (see Figure 7), a companion with a  $\Delta\text{mag} = 1.4$  and a separation of 70 mas is identified.

Combining this data with the USNO astrometric data, we find that each of these WD components is massive ( $\sim 1.1 - 1.4 M_{\odot}$ ). There is some discrepancy when combining the two datasets in that the  $\Delta\text{mag}$  determined by FGS at V is too large to produce the small photocentric shift seen in the USNO data. This can be partially rectified if the two WDs are of different temperatures such that the  $\Delta\text{mag}$  at R (the filter used to detect the astrometric perturbation) is smaller. Another visit using FGS is warranted to confirm the initial  $\Delta\text{mag}$  that was determined and to obtain another data point on the orbit. Further evaluation should allow for a pair of well constrained WD dynamical masses that will anchor the high-mass end of the M-R diagram.



## 5. Conclusions

With only three WDs having dynamical mass determinations known to better than 5%, it is vital that additional WD systems are identified with orbital parameters conducive to accurate orbit determinations. In addition, to remove any uncertain variables associated with common envelope phase systems, the WD systems should have evolved essentially as single stars. Co-author Nelan has identified two DD systems (WD 1639+153 and WD 1818+126) with  $\sim 20$  year periods as well as another DD system (WD 0727+483) with a  $\sim 18$  year period. In a relatively short time, including the resolved system presented here (WD 1132+470), these objects will provide eight new empirical points on the M-R diagram. Also, co-author Nelan has identified an additional four DD systems that were only marginally resolved with FGS such that no accurate orbital determinations were possible. Should astrometric resolving capabilities improve in the future (e.g., via *Space Interferometry Mission*), these systems would be resolvable and accurate orbits could be mapped. Thus, we can be confident that the number of accurate dynamical WD masses will substantially increase. We plan to continue FGS observations of new nearby WDs to further populate the M-R Diagram and better scrutinize the theoretical M-R relation.

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